Advanced Topics: Scaling, Exploits, and Security

Mini-Lecture (30 minutes)

Prof. Dr. Jörg Osterrieder · Blockchain, Crypto Economy & NFTs · Spring 2026

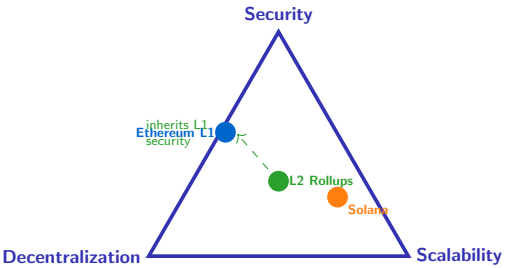
Learning Objectives:

1. **[Understand]** Explain how L2 rollups solve the scalability trilemma
2. **[Analyze]** Compare optimistic and ZK-rollups on security and finality
3. **[Apply]** Trace a flash loan attack and identify the exploit vector
4. **[Evaluate]** Apply the 5-Layer Security Framework to evaluate protocol risk

Topics: Layer-2 Scaling · Flash Loans · Smart Contract Security · MEV · Bridge Attacks

By the end of this session you will be able to reason about protocol design trade-offs and evaluate DeFi security postures.

The Scalability Trilemma and L2 Solutions



Three L2 Approaches:

Type	How it Works
Rollups	Off-chain execution; data + proof posted to L1. Optimistic or ZK.
Sidechains	Independent chain with own validators (e.g., Polygon).
State Channels	Bilateral off-chain; settle on-chain at close (e.g., Lightning).

Key Insight

Rollups inherit Ethereum's security while achieving 10–100× throughput gains.

Trilemma: no single layer optimizes all three — L2 solutions trade off one property to gain another.

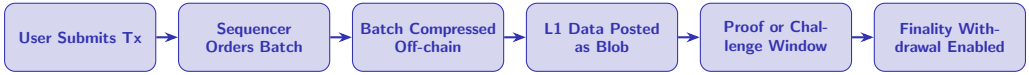
Optimistic vs. ZK-Rollups: Head-to-Head

Dimension	Optimistic Rollup	ZK-Rollup
How it works	Assume batch valid; fraud proof submitted by watchers if invalid	Validity proof (ZK-SNARK/STARK) generated off-chain, verified on L1
Finality	∼**7 days** (challenge window must elapse)	**Minutes** (proof verified on L1 immediately)
Security model	1-of-N honest verifier assumed to submit fraud proof	Cryptographic soundness; trustless (no honesty assumption)
Examples	Arbitrum, Optimism, Base	Starknet, zkSync Era, Scroll
Key trade-off	EVM-compatible, easy migration; but slow L1 withdrawals	Fast finality; but high proving cost and EVM complexity

Post-Dencun (EIP-4844, March 2024): Both rollup types now post data as *blob transactions* rather than calldata, reducing L1 data costs by up to 98%. Base fees dropped from $0.50 to $0.005 per transaction overnight.

Optimistic rollups dominate TVL today (Arbitrum, Base); ZK-rollups are growing as proving costs fall with hardware acceleration.

How a Rollup Works: Transaction Lifecycle



Optimistic: Fraud proof window = 7 days before withdrawal to L1

ZK: Validity proof generated in minutes, then immediately final on L1

Centralisation Risk

Most rollups today use a **single sequencer** – a bottleneck and censorship risk. Decentralised sequencer sets are an active research area.

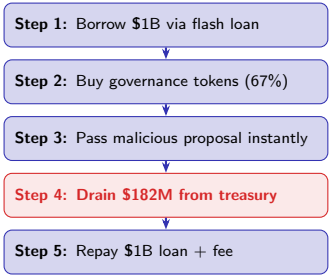
Dencun Impact (March 2024)

Blob transactions (EIP-4844) cut rollup L1 data costs by up to 98%. Base daily fees dropped from **$**1M+ to under **$**20K.

The sequencer is the current centralisation risk in most rollups – decentralised sequencers are an active research area (Espresso, Astria).

Flash Loans: Zero-Capital Attacks

Beanstalk Attack (April 2022)



All in one transaction ($\approx$13 seconds)

What Makes Flash Loans Dangerous?

- **Zero capital required:** Any amount, no collateral
- **Atomic:** Borrow, exploit, repay in one tx
- **Reversible on failure:** If repayment fails, entire tx reverts – attacker loses only gas
- **Speed:** Governance, oracle manipulation in $<$30 seconds

Flash Loan Attack Patterns:

1. **Oracle manipulation:** Inflate price on DEX, exploit lending protocol
2. **Governance attacks:** Instant majority for malicious vote (Beanstalk)
3. **Arbitrage:** Legitimate – capture price diffs across pools
4. **Collateral swaps:** Replace collateral in a single block

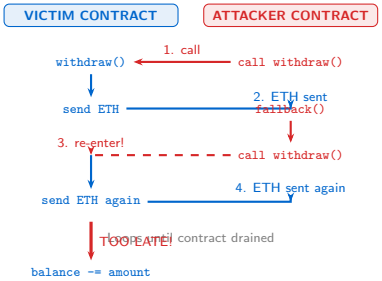
Defence

Time-weighted average prices (TWAPs), timelocks on governance, multi-block oracle readings.

Flash loans are not inherently malicious – they enable arbitrage, collateral swaps, and self-liquidation. The attack vector is the exploited protocol's logic.

Smart Contract Vulnerabilities: Reentrancy

The Call Sequence (Recursive Drain)



The Bug: Wrong Execution Order

- **Vulnerable pattern:** Send ETH *before* updating balance
- **Attacker's trick:** `fallback()` re-calls `withdraw()` before balance is updated
- **Result:** Contract drained completely

The DAO Hack (2016)

3.6M ETH stolen (≈$60M at the time) using exactly this pattern. Led to Ethereum hard fork creating ETH and ETC.

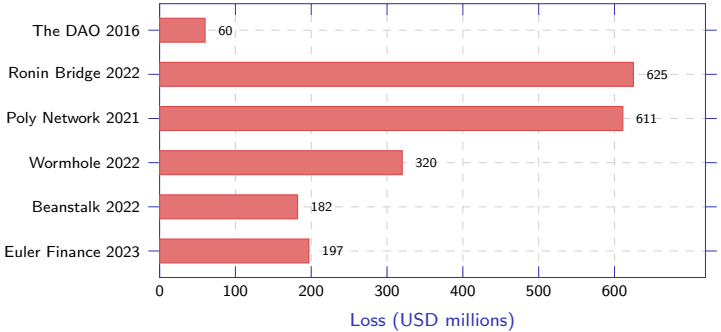
Fix: Checks-Effects-Interactions Pattern

1. **Check:** `require(balance[msg.sender] > 0)`
2. **Effect:** `balance[msg.sender] = 0` *(first!)*
3. **Interact:** `msg.sender.call{value: amount}("")`

Also: use `ReentrancyGuard` (OpenZeppelin) or `nonReentrant` modifier.

Reentrancy remains in the OWASP Smart Contract Top 10 nearly a decade after The DAO. The fix is simple – the pattern is easy to overlook under deadline pressure.

Major Smart Contract Exploits: The Billion-Dollar Bug Timeline



Attack Vectors:

DAO	Reentrancy
Poly	Access control
Ronin	Key theft (5/9)
Wormhole	Signature bug
Beanstalk	Flash loan
Euler	Flash loan + bug

Total

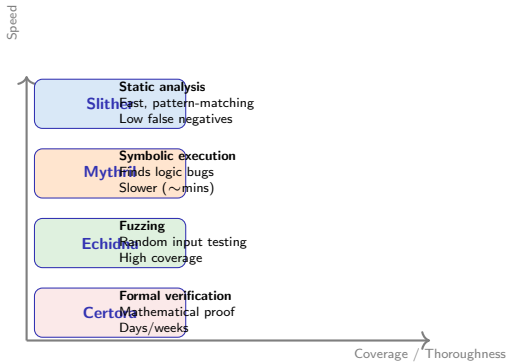
shown: $1.995B

DeFi hacks 2016–2024: >**$3 billion**

No single attack type dominates – bridge attacks, access control failures, and flash loan exploits each account for major losses.

Security Tools and the Audit Process

Four Complementary Security Tools:



5-Step Audit Pipeline:

1. **Automated Scan** (Slither, Mythril)
   Catch known patterns in minutes
2. **Fuzz Testing** (Echidna)
   Explore edge cases with random inputs
3. **Manual Code Review**
   Senior auditors: logic & business risk
4. **Formal Verification** (Certora)
   Prove invariants mathematically
5. **Bug Bounty** (Immunefi, HackerOne)
   Crowdsource ongoing discovery

Warning

A single audit is insufficient. The Euler Finance hack ($197M) occurred despite a prior audit. Continuous monitoring is essential.

Security is a process, not a one-time event. The cost of a thorough audit ($50–500K) is trivial compared to the cost of a hack.

MEV, Bridges, and Cross-Chain Risk

Maximal Extractable Value (MEV)

MEV is profit extracted by block producers (or searchers) by reordering, inserting, or censoring transactions.

- **Sandwich attack:** Searcher sees large pending swap; inserts buy *before* it and sell *after* – user gets a worse price
- **Front-running:** Copy a profitable arbitrage tx with higher gas
- **Back-running:** Place tx immediately after a known large trade
- **Scale:** >$600M extracted on Ethereum (2020–2025, cumulative)

Why Bridges Are the Weakest Link

Bridges lock assets on one chain and mint equivalents on another – a concentrated honeypot.

Bridge	Loss	Attack
Ronin	$625M	Validator key theft (5 of 9)
Wormhole	$320M	Signature verification bug
Nomad	$190M	Merkle root initialisation
Harmony	$100M	2-of-5 multisig compromised

Mitigations

MEV-Boost (PBS), commit-reveal schemes, private mempools (Flashbots Protect), slippage limits.

Root Cause Pattern

Bridges concentrate trust in few validators or rely on bespoke cryptography – the antithesis of the security-by-decentralisation model of L1s.

MEV and bridge attacks represent systemic risks that grow with DeFi TVL – they scale with the value they can extract.

Key Takeaways

1. **L2 rollups solve the scalability trilemma by inheriting L1 security.**
   The Dencun upgrade (March 2024, EIP-4844 blob transactions) cut rollup fees by up to 98%. Optimistic rollups have 7-day withdrawal delays; ZK-rollups settle in minutes with cryptographic proofs.

2. **Flash loans enable zero-capital attacks – atomic, reversible, and devastatingly fast.**
   The Beanstalk exploit ($182M) borrowed $1B, seized governance, and drained the treasury in a single 13-second transaction. Defence requires TWAPs, governance timelocks, and multi-block oracles.

3. **Over $3 billion lost to smart contract exploits – reentrancy, oracle manipulation, bridge attacks.**
   The DAO (2016) established reentrancy as a foundational vulnerability. Bridges are the single largest attack surface, concentrating trust that L1s deliberately distribute.

4. **Defence requires multiple layers: automated scanning + manual audit + bug bounties + formal verification.**
   No single tool catches all bugs. A rigorous 5-step pipeline (Scan $\rightarrow$ Fuzz $\rightarrow$ Review $\rightarrow$ Verify $\rightarrow$ Bounty) combined with on-chain monitoring is the industry standard.

Cryptoeconomic design must account for adversarial conditions: assume attackers are rational, well-capitalised, and faster than you.

Quiz: Advanced Topics (Q1–Q5)

Q1. [Understand] What three properties does the scalability trilemma force a trade-off between?
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Answer: C – The fix is Checks-Effects-Interactions: update state *before* making any external calls.

Answers hidden initially – reveal with presenter click. All questions map directly to the four learning objectives.

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Answer: B – CEI updates state (balance = 0) before the external call, so any re-entrant `withdraw()` sees zero balance and reverts.

Score 8–10: Expert level. 5–7: Solid foundation. Below 5: Review reentrancy, rollup mechanics, and flash loan atomicity.